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14. ABSTRACT
We have demonstrated a mechanism of tunable optical delay that takes advantage of the strong Coulomb interactions between excitons and free carriers and uses optical injection of free carriers to broaden and bleach an exciton absorption resonance. Fractional delay exceeding 200% has been obtained for an 8 ps optical pulse propagating near the heavy-hole excitonic transition in a GaAs quantum well (QW). We have also developed a scheme of using trions in mixed-type QW to realize a lamda-type three-level system for electron spin coherence in semiconductors.

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Final Progress Report

Slow light and adiabatic bandwidth variation in semiconductor nanostructures

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1. Objectives and approaches

Objectives:

i) Investigate and explore various physical mechanisms and material systems for slow light processes in semiconductors.

ii) Demonstrate tunable optical delays in semiconductors with a delay-bandwidth product of 200%.

Approaches:

i) Use electromagnetically induced transparency (EIT) from electron spin coherence in semiconductor quantum wells for slow light and explore adiabatic bandwidth variation to further improve the delay bandwidth product.

ii) Use carrier-induced exciton dephasing as a nonlinear mechanism to realize tunable optical delay in semiconductor quantum wells.

2. Summary of important accomplishment

We have developed a scheme of using trions in mixed quantum well (QW) structures to realize a Λ-type three-level system for electron spin coherence in semiconductors. Experimental studies in GaAs QW have demonstrated coherent Raman resonance from the electron spin coherence, which can be viewed as a manifestation of EIT. We have also carried out extensive theoretical simulations to explore the use of adiabatic bandwidth to improve the delay-bandwidth product that can be achieved in a semiconductor EIT system.

We have demonstrated a mechanism of tunable optical delay that takes advantage of the strong Coulomb interactions between excitons and free carriers and uses optical injection of free carriers to broaden and bleach an exciton absorption resonance. Fractional delay exceeding 200% has been obtained for an 8 ps optical pulse propagating near the heavy-hole excitonic transition in a GaAs QW structure. Tunable optical delay based on optical injection of free carriers avoids strong absorption of the pump beam and is also robust against variations in the frequency of the pump beam

a) Λ-type three-level system for electron spin coherence

We have pursued an experimental program to realize electromagnetically induced transparency (EIT) from electron spin coherence in semiconductors. Our earlier efforts have focused on a scheme of V-type three-level systems. There are two limitations for V-type EIT schemes. First of all, absorption of the control beam is unavoidable in such a scheme. Secondly, the lifetime of the electron spin coherence is limited by the radiative lifetime. A more ideal system, which overcomes these limitations, is a Λ-type three-level system, in which the two lower states are the electron spin states.

To realize a Λ-type three-level system, we have used a GaAs/AlAs mixed-type QW (MTQW) system. As shown in Fig. 1a, the MTQW structure consists of narrow and wide GaAs wells separated by an AlAs barrier. Electrons photoexcited above the band gap in the narrow well (NW) can thermalize and transfer via the X-valley in the AlAs barrier to the conduction band of the wide well (WW). The holes, however, remain confined in the NW, preventing recombination with the electrons. Optical excitation of electron-hole pairs in the NW controls the electron density that collects in the WW. For electrons in the WW, a Λ-type three-level system can be realized by coupling the spin-up and spin-down electron states to a trion state X^-, defined as an exciton bound to an electron (see Fig. 1b).

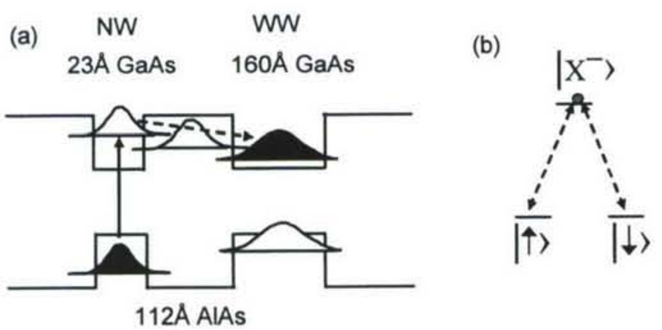

Fig. 1 (a) Schematic of a mixed-type GaAs/AlAs quantum well structure. (b) A Λ-type three-level system formed by spin-up and spin-down electron states coupling to a trion state, X^-, via two dipole optical transitions.

The MTQW structure used in our studies consists of four periods of narrow (23Å) and wide (160Å) GaAs QWs separated by 112Å AlAs barriers (see Fig 1a), with the substrate removed for transmission. The narrow well (NW) is a type-II QW, in which the bottom of the conduction band is energetically higher than the X-valley in the AlAs barrier. Figure 2 shows the differential transmission (DT) spectrum as a function of the pump-probe detuning, where a pump beam with a fixed frequency is tuned to the trion absorption resonance. Two resonances symmetrically offset from zero detuning are observed. The energy separation between the two resonances is 2.7 GHz, which is twice the electron Zeeman splitting and is in good agreement with the expected electron g-factor, $|g_e|=0.27$. The linewidth of the resonances corresponds to a spin decoherence rate as small as $\gamma_s/2\pi=75$ MHz (or a spin decoherence time of 2 ns), significantly smaller than the electron spin decoherence rate of 200 MHz obtained in earlier studies of a V-type three-level system. The resonances arise from destructive interference induced by the electron spin coherence and can be viewed essentially as a manifestation of EIT. The inset shows the results of theoretical calculation based on the use of density matrix equations. The calculated DT response is in qualitative agreement with the experimental observation.

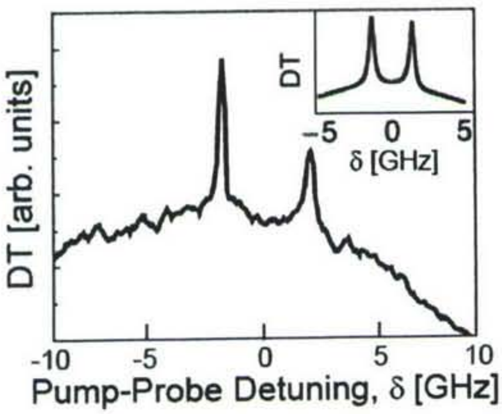

Fig. 2 DT responses obtained at B=0.3 T and T=10 K, with the pump energy placed at trion absorption resonance. Inset shows the theoretical calculation of the DT response as discussed in the text.

b) Tunable optical delay via carrier induced exciton dephasing

We have demonstrated tunable optical delay with a delay-bandwidth product exceeding 200% by using carried-induced exciton dephasing in a GaAs QW structure. In this scheme, a pump beam excites free carriers above the band gap. Strong Coulomb interactions between excitons and free carriers induce a large broadening in the exciton resonance, leading to significant modifications in the group velocity of a signal beam propagating near the exciton resonance.

When an optical pulse with frequency, ν, propagates in a dielectric medium, the phase velocity is *c*/*n*, where *n* is the refractive index, and the group velocity is given by

$$v_g = \frac{c}{n + \nu(dn/d\nu)}. \qquad (1)$$

Near an absorption resonance, the group velocity depends strongly on both the spectral lineshape as well as the transition strength associated with the resonance. Varying the spectral lineshape as well as the transition strength modifies the group velocity, resulting effectively in a tunable optical delay.

The experimental studies were carried out in a high quality undoped (001) GaAs/$Al_{0.3}Ga_{0.7}As$ QW sample grown by molecular beam epitaxy. The sample contains 50 periods of 17.5 nm GaAs wells and 15 nm $Al_{0.3}Ga_{0.7}As$ barriers. To illustrate how the exciton absorption affects the group velocity of a nearly resonant optical pulse, we plot in Fig. 3 the result of a time-of-flight measurement of a weak signal pulse after its transmission through the QW sample (no free carrier injection was used in these measurements). As shown in Fig. 3, the signal pulse becomes more delayed, i.e. arrives at a later time, as the central wavelength of the pulse approaches the heavy-hole (HH) resonance.

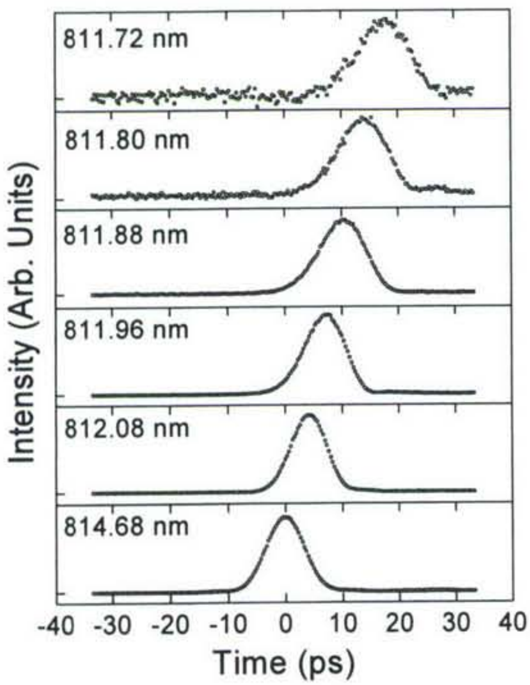

Fig. 3 Time-of-flight measurements of the signal pulse after its transmission through the QW sample. The central wavelength of the signal pulse is indicated in each figure. The results were obtained at 20 K and with the sum frequency generation shown schematically in Fig. 1. Note that t=0 was set to the peak of the signal pulse when the pulse was tuned far below the HH exciton resonance. The average intensity of the signal pulse is 0.2 W/cm^2.

Figure 4 compares directly time-of-flight measurements of the signal pulse after its transmission through the QW sample with and without the optical injection of free carriers by a pump beam. For clarity of display, normalized intensity is shown in Fig. 4. The free carrier injection leads to a 2-fold increase in the signal transmission for Fig. 4(a) and an 8-fold increase in the signal transmission for Fig. 4(b). Fractional pulse delay (the ratio of the pulse delay over the incident pulse duration) exceeding 200% has been observed at T=20 K [see Fig. 4(b)]. Smaller fractional delays have been observed at higher temperatures. The fractional delays observed in Fig. 4 agree well with what is expected for the group delay induced near the HH exciton absorption resonance shown in Fig. 3. The pulse delay, however, is also accompanied by a significant broadening or reshaping of the temporal line shape of the signal pulse. For both Fig. 4(a) and Fig. 4(b), the pulse broadening is nearly 30% of the incident pulse width. The primary limitation for achieving greater fractional delay is the strong absorption of the signal beam near the exciton resonance since the fractional group delay scales with αl where α is the absorption coefficient and l is the sample length. The bandwidth of the tunable optical delay is limited by the spectral linewidth of the exciton resonance. Much greater bandwidth can be achieved at higher temperature or with exciton resonances that are strongly inhomogeneously broadened. For example, a delay bandwidth exceeding 300 GHz can be achieved with an exciton absorption linewidth of 5 meV.

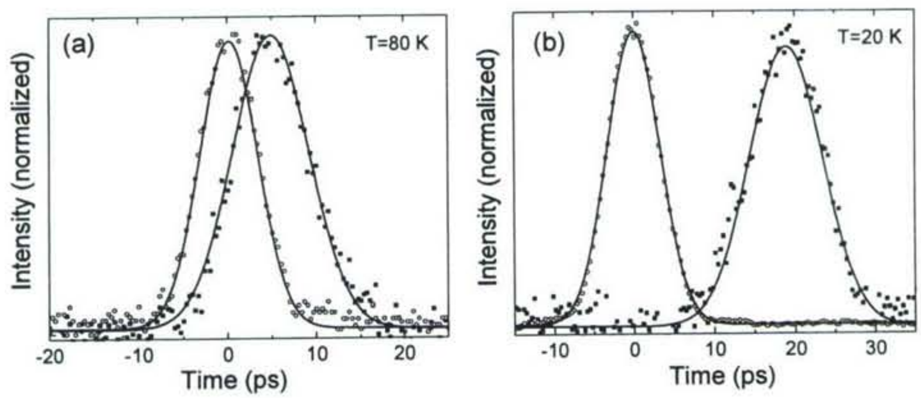

FIG. 4 Time-of flight measurements of a signal pulse after its transmission through the QW sample with (open circles) and without (squares) free carrier injection by a pump beam at λ=795 nm. (a) T=80 K and I_{pump}=2 mW. (b) T=20 K and I_{pump}=4 mW. The solid lines are numerical fit to a Gaussian. The central wavelength of the signal pulse is at λ=815.69 nm and λ=811.72 nm for (a) and (b), respectively. Note that here, t=0 was set to the peak of the signal pulse in the presence of optical injection of free carriers.

3. Publication

JOURNAL ARTICLES (refereed):

1) Susanta Sarkar, P.C. Ku, C. J. Chang-Hasnain, N.H. Kwong, R. Binder, and Hailin Wang, "Inducing electron spin coherence in a quantum well waveguide: Spin coherence without spin precession," Phys. Rev. B72, 035343 (2005).
2) Susanta Sarkar, Yan Guo, and Hailin Wang, *"Tunable optical delay via carrier induced exciton dephasing,"* Opt. Express **14**, 2845 (2006).
3) Shannon O'Leary, Hailin Wang, and J. Prineas, *"Coherent Zeeman resonance from electron spin coherence in a mixed type GaAs quantum wells,"* accepted for Opt. Lett. (2006).

4) S. W. Chang, S. L. Chuang, Haillin Wang, C. J. Chang-Hasnain, "*Slow Light Using Spin Coherence and V-type EIT in [110] Strained Quantum Well*," accepted for J. Opt. Soc. Am. B (2006).

INVITED TALKS AT INTERNATIONAL CONFERENCES AND WORKSHOIPS:

1. *Electromagnetically induced transparency and exciton coherences*, Physics of Quantum Electronics'2006 (Snowbird, Utah, Jan. 2006).
2. *Electromagnetically induced transparency in semiconductors*, Photonics West (San Jose, CA, Jan. 2006).
3. *Slow light in semiconductor nanostructures,* OSA Topical Meeting on Slow and Fast Light (Utah, July, 2006).
4. *Slow light in semiconductor nanostructures,* Berkeley Nano-Optics Workshop and Summer School (Berkeley, Aug. 2006).

CONFERENCE PRESENTATIONS WITH PROCEEDINGS (refereed):

1. Shannon O'Leary, John Prineas, and Hailin Wang, "*A Λ-Type System for Electron Spins in a Mixed-Type GaAs/AlAs Quantum Well*," Proceedings of Quantum electronics and laser science conference, OSA Technical Digest (Long Beach, 2006).
2. Yan Guo, Susanta Sarkar, and Hailin Wang, "*Pulse propagation near exciton resonance: Anomalous transition between slow and fast light*," Proceedings of Conference on lasers and electro-optics, OSA Technical Digest (Baltimore, 2007), submitted.

BOOK CHAPTER:

Mark Phillips and Hailin Wang, "*Electromagnetically induced transparency in semiconductors,*" in Nonequilibrium Dynamics of Semiconductor and Nanostructures, Edited by K.T. Tzen, (Marcel Dekker, New York 2005).

4. Scientific Personnel

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Susanta Sarkar graduated with PhD in physics in June 2006.

5. Report of inventions

No patents were filed.